2.4 GHz and 5 GHz WLAN: Competing or Complementary?

*Wi-Fi™ and 802.11a are not a one-for-one trade off. They are complementary technologies and will coexist in future enterprise environments.*

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**Abstract**

With the 1999 introduction of Wi-Fi™ (IEEE-802.11b), the 2.4 GHz wireless local area network (WLAN) standard, the WLAN market finally began to experience the exciting growth levels that many have expected for so long. Now, with 802.11g speed enhancements to Wi-Fi, and 5 GHz solutions on the horizon—both promising new levels of throughput and benefits—users must be able to make an educated choice between deploying 2.4 GHz-only networks (Wi-Fi + 802.11g), 5 GHz-only networks, or a combination of both. This paper focuses on helping current and potential WLAN technology users in the enterprise segment evaluate the different technologies. In this paper, we provide an objective assessment of the different technologies according to appropriate market and business considerations, performance capabilities, deployment considerations, and technical characteristics.

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Executive Summary

As the WLAN market begins to achieve momentum, several technologies are vying for market awareness and unit volume dominance: Wi-Fi and its IEEE-802.11g speed extension, and IEEE-802.11a. Although there are many more WLAN technologies and standards worldwide, this paper assesses the benefits and considerations of only these two, as we believe, based on market momentum, they will be more widely deployed than other standards.

First, allow us to establish our credibility. Mobilian Corporation is currently bringing a product to market in the 2.4 GHz space that integrates Wi-Fi and Bluetooth™ in a single chipset. We are also developing a system-level 5 GHz, 802.11a-compliant product. Therefore, we consider ourselves supporters of both WLAN technologies, and believe we can provide an unbiased, comparative assessment.

Each technology has major points of differentiation, but neither is a clear “winner” based solely on operational criteria. Likewise, the two technologies are not a simple “copy / paste” for each other. Companies with existing Wi-Fi/802.11b networks cannot simply deploy a new 802.11a network on the Wi-Fi access points (APs), and expect to have similar coverage with 802.11a’s 54 Megabits per second (Mbps) data rate. The physics and operational characteristics simply don’t work that way.

Also, the two technologies are not mutually exclusive, and will likely never become so. In fact, given their different operating characteristics, many usage models would benefit greatly from a dual standard deployment model. Wi-Fi’s range and sustainable 11 Mbps data rate could be complemented with 802.11a’s space-concentrated, 54 Mbps data rate. Or, instead of a “big bang” deployment of new 802.11a infrastructure and clients, an incremental deployment could be used, saving dollars and increasing the return on investment in Wi-Fi.

The standards have very different value propositions, which touch on different end-user values by segments, usage models, applications, and existing WLAN equipment. There is no “Executive Summary” of the possible deployments for every situation. However, we believe the enterprise market will likely have deployments of both technologies for a good number of years, and the home will likely deploy Wi-Fi for internet sharing and voice, and a higher bandwidth standard for video sharing.

The remainder of this paper examines the technologies’ differences. In Table 1, we provide a summary of several key differences, but we recommend reading the paper in its entirety to fully understand the key differentiators and reap the most benefit from WLAN installations.

Table 1: Key Differences Between Wi-Fi, 802.11g, and 802.11a

<table>
<thead>
<tr>
<th>Standard</th>
<th>Modulation &amp; Coding</th>
<th>Spectrum Unification</th>
<th>Available Spectrum</th>
<th>Data Rate3</th>
<th>Throughput</th>
<th>Range4 &amp; Corresponding Data Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wi-Fi</td>
<td>DSSS / CCK</td>
<td>Yes</td>
<td>83.5 MHz</td>
<td>11 Mbps</td>
<td>5-7 Mbps</td>
<td>100 m² @ 11 Mbps</td>
</tr>
<tr>
<td>802.11gOFDM</td>
<td>OFDM</td>
<td>Yes</td>
<td>83.5 MHz</td>
<td>24 Mbps</td>
<td>10-11 Mbps</td>
<td>100 m² @ 12 Mbps</td>
</tr>
<tr>
<td>802.11gPBCC</td>
<td>DSSS / PBCC</td>
<td>Yes</td>
<td>83.5 MHz</td>
<td>22 Mbps</td>
<td>10-11 Mbps</td>
<td>100 m² @ 11 Mbps</td>
</tr>
<tr>
<td>802.11a</td>
<td>OFDM</td>
<td>No</td>
<td>300 MHz</td>
<td>54 Mbps</td>
<td>31 Mbps</td>
<td>50 m² @ 9 Mbps</td>
</tr>
</tbody>
</table>

1 More information on Mobilian’s first product, TrueRadio™, can be found on Mobilian’s web site at www.mobilian.com.
3 Data Rate— See Appendix B—WLAN Throughput Calculations. Both 802.11a and 802.11gOFDM are capable of 54 Mbps throughput. 802.11gOFDM is shown at 24 Mbps to compare to 802.11gPBCC. 802.11gOFDM & 802.11gPBCC chipsets are still unapproved under FCC rule 15.247 as of publishing of this white paper.
4 Range and Corresponding Data Rate— Assumes constant operational variables for all standards. Common receiver sensitivity, 16 dBm transmitter (40 mW), “light office” path loss model, and similar end-point data rates to Wi-Fi (11 Mbps for Wi-Fi & 802.11gPBCC; 12 Mbps for 802.11gOFDM and 9 Mbps for 802.11a). See Appendix A—Comparison of radio wave propagation at 2.4 and 5 GHz frequencies for further discussion.
1 Wireless LAN Market - Background

The wireless local area network (WLAN) market is in the early stages of what appears to be mass adoption. In a recent Gartner Group survey of midsize and large businesses, 50 percent expect WLANs to be deployed at a minimum of one of their company's locations in the next two years [GG01]. This rapid adoption makes the WLAN market very attractive to many companies who have historically viewed it as too specialized and small to be meaningful. With the ratification of the 11 Mbps 802.11b standard (Wi-Fi) in the second half of 1999, guaranteed interoperability and declining cost points became a reality, and traditional tier 1 networking players such as Cisco, Lucent, 3COM, Intel, and Texas Instruments entered the WLAN market. This was in addition to existing players such as Symbol, Intermec, and Intersil (Harris Semiconductor at the time). As the market has entered this latest phase, the competitive environment has grown in intensity, driving rapid innovation and subsequent benefits in costs and performance.

The WLAN market is comprised of several competing technologies, each with different operating characteristics such as modulation type, data throughput, frequency band, and transmit power. These WLAN standards include:
- HomeRF and HomeRF 2.0 (Wide-band Frequency Hopping (WBFH));
- IEEE-802.11FH/DS (1997);
- Wi-Fi (IEEE-802.11b 1999);
- IEEE-802.11gOFDM (Wi-Fi speed extension proposal);
- IEEE-802.11gPBCC (Wi-Fi speed extension proposal);
- MMAC (HiSWANa)
- HiperLAN/2; and
- IEEE-802.11a.

Two of these WLAN technologies are expected to be dominant over the next five years: Wi-Fi (and its 802.11g extension), and 802.11a. A third, whose future is still somewhat uncertain, is HiperLAN/2.

Both 802.11b and 802.11a were proposed and ratified out of the US-based Institute of Electrical and Electronic Engineers (IEEE), but use different unlicensed frequency bands. The Wi-Fi standard can achieve raw data rates of 11Mbps, has a range of about 100 meters, and uses the Industrial, Scientific, and Medical (ISM) band between 2.4000 – 2.4835 GHz.

The 802.11a standard uses the Unlicensed National Information Infrastructure (U-NII) and ISM bands in the United States, can achieve raw data rates of up to 54 Mbps for short distances, and has a range of about 50 meters at a data rate comparable to Wi-Fi (about 912 Mbps). The 5 GHz “band” is actually a conglomerate of several bands: 5.150 – 5.250, 5.250 – 5.350, 5.470 – 5.725, and 5.725 – 5.875.

The adoption and market ramp of these two technologies is difficult to forecast. Based on multiple analysts’ market forecasts Wi-Fi’s market momentum and its 802.11g speed extensions will likely carry it to unit volume dominance for the next 34 years. Furthermore, Wi-Fi’s popularity will continue to drive down costs, and Wi-Fi certified interoperability testing will continue to be a catalyst for widespread adoption.

IEEE-802.11a will first see product samples this year (2001), but will not begin to have a meaningful ramp until late 2002 to mid-2003. This is caused by many factors, including its “cutting edge” status as a new and leading technology. (This will be attractive to a small segment of buyers, primarily home and SOHO, but will not appeal to the more risk-averse enterprise segments, or the more mainstream mass markets.) Also, with only one, or possibly two, products sampling in 2001, it is unlikely that any interoperability program will be ratified or viable.

The real question though, is how corporate IT Managers, small business owners, and home users choose between one or the other—Wi-Fi and its 802.11g speed extensions, or 5 GHz— or adopt a mixed environment. In the rest of this paper, we address the issues relevant to making this decision, and provide meaningful comparisons of the technologies’ different characteristics.

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5 Many industry participants consider Bluetooth a WLAN technology. This is not consistent with the Bluetooth SIG’s opinion, however, which defines it as a “cable replacement” and wireless personal area network technology. Mobilian agrees with the Bluetooth SIG for this reason, and for other technical reasons, which limit Bluetooth’s ability to function effectively as a WLAN.
2 Interference Concerns

A common concern to all unlicensed bands is interference between the devices using the spectrum. This is absolutely a valid concern, and has historically affected all the unlicensed bands: 49 MHz, 330 MHz, 900 MHz, 2.4 GHz, etc. The lifecycle of the devices using an unlicensed band generally follows a four-step process based on technical innovation, from a sparse device population to many devices sharing the spectrum:

- **Phase 1:** The band is used primarily by scientific or military systems, not by commercial devices.
- **Phase 2:** The first commercial devices capable of using the band enter the market and are very expensive because corresponding development costs are very high.
- **Phase 3:** Relatively common devices begin using the spectrum because technical innovation has decreased development costs, thus lowering price points.
- **Phase 4:** The technology that uses the band becomes available to many devices, driving prices down, device count up, and increasing the potential for interference.

Based on these historical precedents, we strongly believe that there will never be an unlicensed band that is indefinitely interference-free. Given the cost of licensed spectrum, free spectrum is, and always will be, very attractive. Therefore, the claim that a technology utilizes “un-crowded spectrum” is not a relevant buying consideration, especially when evaluating 2.4 and 5 GHz WLAN technology. This is not a decision that should be driven by moving from one band to the next with each technical innovation— that could become very expensive. Instead, it's a decision that should be driven by how suitable the solution is to the user's technical needs. Technical and market innovation will address, and in large part have already addressed, any valid interference concerns.

Furthermore, even today, both the 2.4 GHz and the 5 GHz bands are subject to overcrowding and interference, and are used by many devices outside WLAN. Table 2 below provides an overview of some of the devices and systems that use each band.

<table>
<thead>
<tr>
<th>Band</th>
<th>Wireless LAN Systems</th>
<th>Other Communication Systems</th>
<th>Non-Communication Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4GHz</td>
<td>HomeRF</td>
<td>802.11a (US)</td>
<td>Microwave ovens</td>
</tr>
<tr>
<td>2.400 – 2.4835</td>
<td>Wi-Fi (802.11b)</td>
<td>Bluetooth</td>
<td>Microwave lighting</td>
</tr>
<tr>
<td>5GHz</td>
<td>802.11a (US)</td>
<td>HiperLAN1 (Europe)</td>
<td>Mobile satellite systems (MSS)</td>
</tr>
<tr>
<td>5.150 – 5.350</td>
<td>HiperLAN2 (Europe)</td>
<td>Earth exploration satellite systems (ESSS)</td>
<td>Radar systems</td>
</tr>
<tr>
<td>5.725 – 5.875</td>
<td>802.11a (US)</td>
<td>HiSWAN (Japan)</td>
<td>Microwave ovens (future – upper band)</td>
</tr>
<tr>
<td>5.725 – 5.875</td>
<td>WLL (shared internet access)</td>
<td>WLL (shared internet access)</td>
<td>WLL (shared internet access)</td>
</tr>
</tbody>
</table>

2.1 Interference in the 2.4 GHz ISM Band

Interference in the 2.4 GHz ISM band is no longer a valid concern; however, at the beginning of the year 2000, there was good reason for concern. This was driven primarily by the potential interference created between Wi-Fi and Bluetooth. Since then, multiple companies have researched the issue and have concluded that if the two technologies are separated by 2 meters or more, there is no significant interference. They also concluded, however, that there is interference when the two are located within 2 meters, and that it can be severe when the two technologies are collocated (as in a combination...
NIC). However, this should NOT be an issue when considering whether or not to deploy 2.4 GHz solutions. There are many solutions to the interference issue coming to market this year… long before any significant problems arise.

These solutions range from modifying the Bluetooth standard so its hop pattern can adapt to the presence of a Wi-Fi network, to recommended best practices and associated technologies from the IEEE and the Bluetooth SIG, to technology solutions requiring no changes to the standards, but that allow unhindered simultaneous operation of collocated Wi-Fi and Bluetooth.

Mobilian Corporation examines both the causes of interference between Wi-Fi and Bluetooth, and the various approaches to its resolution, in two white papers located on the Mobilian web site at www.mobilian.com.

### 3 Throughput

An important purchasing consideration for any networking technology is the amount of bandwidth, data rate, or throughput, it provides to each network user, and how well that throughput can support the applications running on the network.

For clarity purposes, data rate means the amount of data able to be sent from one node on the wireless network to another, within a given timeframe—usually seconds (11 megabits per sec = 11 Mbps). Furthermore, the difference between data rate and throughput is the amount of raw bits that travel from one node to another, in comparison to the bits representing the message content. This difference is determined by a number of factors including the latency inherent in the PHY components of the radio, the overhead and acknowledgement information that accompany every transmission, and pauses between transmissions. A comparison table of the wireless networks at hand and several wired benchmarks is shown in Table 3.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Data Rate</th>
<th>Actual Throughput</th>
<th>Shared Among Users?</th>
<th>Estimated Time to Download 100 MB file (Actual Throughput)</th>
</tr>
</thead>
<tbody>
<tr>
<td>56.6 Kbps Modem</td>
<td>56.6 Kbps</td>
<td>56.6 Kbps</td>
<td>No</td>
<td>4 hours</td>
</tr>
<tr>
<td>10/100 Ethernet</td>
<td>100 Mbps</td>
<td>100 Mbps</td>
<td>Yes</td>
<td>8 seconds</td>
</tr>
<tr>
<td>T1 line</td>
<td>1.536 Mbps</td>
<td>1.536 Mbps</td>
<td>Yes</td>
<td>8 minutes 41 seconds</td>
</tr>
<tr>
<td>Wi-Fi</td>
<td>11 Mbps</td>
<td>5-7 Mbps</td>
<td>Yes</td>
<td>2 minutes 8 seconds</td>
</tr>
<tr>
<td>802.11g OFDM</td>
<td>24 Mbps</td>
<td>10-11 Mbps</td>
<td>Yes</td>
<td>1 minute 13 seconds</td>
</tr>
<tr>
<td>802.11g PBCC</td>
<td>22 Mbps</td>
<td>10-11 Mbps</td>
<td>Yes</td>
<td>1 minute 14 seconds</td>
</tr>
<tr>
<td>802.11a</td>
<td>54 Mbps</td>
<td>31 Mbps</td>
<td>Yes</td>
<td>26 seconds</td>
</tr>
</tbody>
</table>

#### 3.1 Throughput - Wi-Fi

Wi-Fi offers an 11 Mbps data rate, which translates into approximately 5.7 Mbps of actual message throughput. This amount is shared among all network users who are using it at precisely the same time, and is managed through a CSMA/CA technique modeled on its Ethernet wired equivalent. As most network traffic is bursty, and only a few users are on the network simultaneously, Wi-Fi network users generally experience very good connectivity speeds. In addition, there are several potential speed increases in store for Wi-Fi, which will come from the IEEE 802.11 Task Group g.

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6 In the past year, Mobilian has helped to define the market’s awareness of, first, the coexistence issue, and second, the potential solutions. These topics have been covered extensively in the press, and very specifically in two Mobilian white papers. Both white papers are available on Mobilian’s web site at www.mobilian.com.

1. **Wi-Fi™ (802.11b) and Bluetooth Simultaneous Operation: Characterizing the Problem** - An overview of the two technologies and why there can be a problem between them.

2. **Coexistence Approaches for Wi-Fi (802.11b) and Bluetooth** - A treatment of potential techniques to resolve the issue. This white paper was recently awarded the first ever "Technical Excellence Award" at the Spring Microsoft Windows Hardware Engineering Conference (WinHEC) in recognition of Mobilian’s “contribution to advancing the computing platform.”

7 See Appendix B—WLAN Throughput Calculations.
3.2 Throughput – 802.11g_{OFDM} & 802.11g_{PBCC}

The IEEE Task Group g (802.11g) is charged to develop a new PHY extension to enhance the performance and possible applications of Wi-Fi compatible networks by increasing the achievable data rate. The IEEE is currently considering two proposals for adoption: 802.11 Packet Binary Convolutional Code (802.11g_{PBCC}), and 802.11 Orthogonal Frequency Division Multiplexing (802.11g_{OFDM}).

Neither technique has been approved for use in the US under FCC Rule 15.247, but the FCC will likely modify the rule to allow whichever technique is recommended. The proposal process has been an arduous one because of the high stakes involved for all participants, but is expected to end prior to the third quarter of 2001. If the task group does not reach a recommendation by this time, the point may be moot, as emerging availability of 802.11a products and applications may erode the 802.11g value proposition.

Using OFDM and 64-Quadrature Amplitude Modulation (QAM), 802.11g_{OFDM} will provide data rate levels equal to those provided by 802.11a OFDM technologies. However, because 802.11g_{OFDM} is required to be backward compatible with Wi-Fi, it is burdened by bits of Wi-Fi's overhead, such as header information. For this reason, it will not likely achieve parity with the data rates possible with 802.11a. For comparison purposes in this paper, we show 802.11g_{OFDM}'s data rate at 24 Mbps, roughly equal to that of 802.11g_{PBCC}.

The 802.11g_{PBCC} technique is defined within the current 802.11b specification, but has not obtained FCC equipment authorization at the speed levels proposed by 802.11g_{PBCC}. The 802.11g_{PBCC} technology uses the same basic technology as Wi-Fi, but modifies the modulation scheme and the FEC slightly to achieve 22 Mbps data rate.

Both 802.11g proposals will continue to use Ethernet-like management techniques common to all 802.11 standards (including 802.11a), and will therefore efficiently share the increased throughput among all users.

3.3 Throughput – 802.11a

The IEEE-802.11a standard is based on OFDM modulation and will theoretically achieve a 54 Mbps data rate, or approximately 31 Mbps of throughput for a single network (see Appendix B—WLAN Throughput Calculations). This easily supports several simultaneous occurrences of streaming video. Additionally, 802.11a nodes share bandwidth efficiently using the same CSMA/CA techniques used in Wi-Fi systems, thus allowing a large number of users access to high wireless data rates.

3.4 Throughput Conclusion

While Wi-Fi provides plenty of throughput for the majority of common office applications in fairly dense user environments, 802.11a and Wi-Fi extensions under IEEE Task Group 802.11g will provide higher throughput, and subsequently support more bandwidth-intensive applications and larger user populations.

Quality of Service (QoS = voice) enhancements to the 802.11 MAC under development within IEEE task group e will enhance the ability of Wi-Fi, 802.11g, and 802.11a to deliver new types of time-critical data, in addition to their traditional data packets. The IEEE 802.11e Task Group recommendations will become commonly available to both the 2.4 GHz and 5 GHz solutions simultaneously, and most subsequently released 802.11 networks will then be able to support them. The higher bandwidth 802.11g and 802.11a standards will support QoS more effectively than Wi-Fi— not only because of higher bandwidth, but also because more unlicensed spectrum will be available to 5 GHz radios. This would allow 5 GHz networks to allocate a certain number of networks to voice only, and others to data. The number of potential simultaneous operating networks is covered in section 7.

4 Signal Range (Decipherable)

While the theories of electromagnetic wave propagation are outside the scope of this paper, the decipherable signal range of every wireless system is governed by the following variables:

1) RF power transmit level – power at which the signal is transmitted;
2) Required Es/N₀ – Signal energy required to recover the transmitted symbol⁸ compared to the environmental noise (Because symbols are shorter at greater throughput levels, they require more energy in the symbol to recover it for the same error rate. This is one reason a WLAN system’s throughput decreases as the distance between the AP and STA grows.);

3) Environment – The physical characteristics of the radio’s environmental surroundings affect the path loss; and

4) Signal Propagation – Physics of the radio spectrum and frequency in which the radio operates.

One of the most fundamental and significant differences between communication systems operating at 2.4 and 5 GHz is the achievable communication range between the AP and the station, and the corresponding service coverage area. Assuming common environments and system operating parameters, systems operating in the 2.4 GHz frequency band offer roughly double the range of those operating in the 5 GHz band, again holding power and throughput constant. This doubled-range is explained by radio wave propagation physics, which dictate that, all other things being equal, a higher frequency signal will have a lesser range than a lower frequency signal [RAP01].

For simplicity’s sake, consider one 802.11a AP compared to one Wi-Fi AP. In a typical cubicle office environment, a 15 dBm Wi-Fi AP’s transmission and reception will cover a circular area with a radius of approximately 100 meters⁹, with an 11 Mbps data rate. This translates into a coverage area of approximately 31,420 square meters (π*100m²) at 11 Mbps. Assuming the RF transmit power and E₀/N₀ are held constant (i.e., same link budget), an 802.11a AP’s coverage equates to a circular area with a radius of roughly 50 meters¹⁰ for comparable data rate (9 Mbps), equaling a coverage area of approximately 7,850 square meters (see Figure 1) [RAP01, JCS01, DUR01].

![Figure 1: Coverage Comparison of Wi-Fi and 802.11a](attachment:coverage.png)

Because of this fundamental difference in signal wave propagation, it is clear that to achieve similar coverage areas, greater numbers of 802.11a APs must be used. Consider the right-most circle in Figure 1. Four 802.11a APs are needed to cover

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⁸ A “symbol” is the technical wireless term for the information contained in the message. A 16 QAM symbol contains 4 bits; a 64 QAM symbol contains 6 bits.

⁹ This assumes an open office environment and uses the A. Kamerman path loss model [Kam99].

¹⁰ [RAP01, JCS01, DUR01] This assumes a conservative 5 GHz path loss. Mobilian research identified various potential 5 GHz path loss models showing decreased range compared to 2.4 GHz solutions of 45%, 50% and 75%. See Appendix A—Comparison of radio wave propagation at 2.4 and 5 GHz frequencies, for further explanation.
the same 30,400 meters squared that one Wi-Fi AP can cover. To reiterate, this increased number of 802.11a APs provides a comparable data rate to Wi-Fi (~9 Mbps) across the entire area, not 802.11a’s highest data rate, 54 Mbps. Further, to cover the entire Wi-Fi area with 802.11a’s high 54 Mbps data rate requires over 40 802.11a APs.

This is the result of a combined effect. Because the $E_s/N_0$ threshold and corresponding BER are more stringent for higher data rate transmit schemes, and because energy dissipates as a signal moves away from the transmitter, the further the receiver is from the transmitter, the more difficult it becomes to decipher a message. IEEE-802.11a provides high data rate (36-54 Mbps) levels close to the AP—within about 10-15 meters—making it attractive for dense user environments that also require high throughput, but its data rates are closer to 9-12 Mbps at ranges over 30-40 meters.

5 Power Considerations, Relative to Data Rate and Signal Range

The previous sections discussed the fact that 802.11a systems are able to achieve about 50% of the range of 2.4 GHz systems, holding operational variables constant (RF transmit power, receiver sensitivity, etc.), and requiring a data rate approximately equal to Wi-Fi’s 11 Mbps (9-12 Mbps). This limitation in range is caused by the more severe path loss of the 5 GHz spectrum, and the stringent $E_s/N_0$ requirements of 802.11a’s higher data rate modulation techniques. However, by increasing power, 802.11a systems can achieve data rates similar to Wi-Fi (9-12 Mbps) at ranges approaching those of 2.4 GHz systems. This requires an increase of approximately 4 times the RF transmit power of an equivalent 2.4 GHz system, or from 40mW to approximately 200 mW\(^1\), and will likely have a negative impact on battery life.

It is a common conclusion that at very close ranges (less than 30-45 feet in a light office environment), an 802.11a station will spend less time in transmit mode due to its high data rates, and therefore expend less energy than a Wi-Fi station burdened with similar data traffic amounts. This is an unclear conclusion however, given the fact that 802.11a’s more complex modulation techniques require greater power to maintain a suitable $E_s/N_0$ (see section 4). With multiple variables in the equation (environment, data rate, etc.), it is hard to know the break-even point at which an 802.11a system burns less energy transmitting the same amount of data as a Wi-Fi system.

This paper does not include an extensive treatment of the effects of efficiency in the RF power amplifier, which is generally significantly worse for OFDM relative to PSK\(^2\); however, efficiency numbers for OFDM are typically 1/3 of the PSK equivalent. As a result, the total power consumption when transmitting 9-12 Mbps OFDM at 5 GHz can be significantly higher than a Wi-Fi equivalent, even at ranges of only 40-50 meters. Therefore, an 802.11a system is more power efficient and well suited for transmitting high data rates over small, densely populated areas, and a Wi-Fi system is more efficient over greater distances.

It is interesting to note that OFDM technology in the 2.4 GHz band will always surpass its 5 GHz counterpart in power efficiency due to the path loss issue. This implies that for users needing high data rates above 10 – 15 meters from an AP, 802.11g\(_{OFDM}\) will likely meet their needs more power efficiently than 802.11a. Again, this implies that 802.11a is most well suited for high concentrations of data-rate intensive users, and Wi-Fi and its 802.11g counterparts are better suited for greater coverage areas.

6 Global Spectrum Unification

Both the Wi-Fi and 802.11a standards were ratified in September of 1999. However, while the Wi-Fi standard and its operating channels have been accepted globally and are supported by many global networking companies, the 5 GHz band allocations and regulations are still in dispute in several countries (see Table 4). This is an important consideration for multi-national companies and international travelers considering a WLAN purchase.

6.1 2.4 GHz - Wi-Fi, 802.11g\(_{OFDM}\), & 802.11g\(_{PBCC}\)

Wi-Fi and its 802.11g speed enhancements operate in the 2.4 GHz ISM band located from 2.400 - 2.4835 GHz. Largely due to the powerful global efforts of the Bluetooth SIG and the IEEE, this unlicensed band is unified in most of the

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\(^1\) 5 GHz U-NII spectrum regulations limit transmit power in each band (see Table 4). The lower bands, in which WLANs operate, are authorized to 200mW between 5.25 and 5.35 GHz, and 40mW between 5.15 and 5.25 GHz.

\(^2\) The peak power for OFDM systems can be much higher than the average power because many independent carriers are summed together in an OFDM system. This forces the RF power amplifier to run at a much less efficient operating point than for PSK systems such as Wi-Fi and 802.11g\(_{PBCC}\).
world. This means that devices using the 2.4 GHz spectrum, and complying with regulatory standards\(^{13}\) will be legal to operate throughout the most of the world.

### 6.2 5 GHz - 802.11a

In the US, the IEEE-802.11a standard can legally operate in the 5.150–5.350 GHz band, and the 5.725–5.825 GHz band. Outside the US, these bands are allocated to primary users and technologies other than WLAN. Additionally, the bands are not unlicensed worldwide, and have different operational requirements. For example, the 5470–5.725 band is not allowed for unlicensed use in the US, but is available in Europe, and conversely, the 5.725–5.825 band is available in the US but not in Europe or Japan (see Table 4). While this is not a problem for solutions contained within a single country, multi-national companies and individuals who travel internationally would be required to maintain different networks in different countries.

<table>
<thead>
<tr>
<th>5 GHz Frequency Band (GHz)</th>
<th>USA &amp; Canada</th>
<th>Europe</th>
<th>France</th>
<th>Spain</th>
<th>Japan</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.150 – 5.250</td>
<td>40 mW</td>
<td>200 mW</td>
<td>200 mW</td>
<td>200 mW</td>
<td>200 mW</td>
</tr>
<tr>
<td>5.250 – 5.350</td>
<td>200 mW</td>
<td>200 mW</td>
<td>200 mW</td>
<td>200 mW</td>
<td>200 mW</td>
</tr>
<tr>
<td>5.470 – 5.725</td>
<td></td>
<td>1 W</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.725 – 5.875</td>
<td></td>
<td>1 W</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Mobilian Corporation

There are several efforts underway to unify the 5 GHz bands globally, but due to the various agencies and groups with technologies operating in the band already, it is unlikely that the band, and consequently technologies using the band, will be unified until the World Radio Conference (WRC) in 2003. Even then this harmonization is not assured, as other users of the bands will lobby for allocations to their own technologies.

The WRC will evaluate the different primary and secondary users and their proposals for common usage, and will issue a recommendation on the final worldwide band allocations and usage models. This recommendation specifies rules by international treaty and includes legal power levels, modulation techniques, and technology. In rare cases, countries have been known to deviate from the WRC guidelines, but this is not expected in these bands.

### 7 Unlicensed Available Spectrum and Spectral Efficiency

Wi-Fi, 802.11g, and 802.11a networks all use network passbands that cannot overlap, thus limiting the number of simultaneously operating networks to the number of available channels within the unlicensed spectrum, divided by the width of the passband. As the number of WLAN users increases and the bandwidth requirements of applications grow, more WLAN infrastructure must be deployed to support the users, and available throughput must increase. Therefore, the amount of unlicensed spectrum available, and the efficiency with which the standard uses the spectrum, are important considerations.

#### 7.1 2.4 GHz - Wi-Fi, 802.11g\textsubscript{OFDM}, & 802.11g\textsubscript{PBCC}

The 2.4 GHz 802.11 standards all require a passband approximately 22 MHz wide for one operating network. Using direct sequence spread spectrum modulation (DSSS), Wi-Fi provides an 11 Mbps data rate to the network users. Thus, the 2.4 GHz band’s 83.5 MHz will support three non-overlapping, simultaneously operating Wi-Fi networks (66/83.5), and roughly 33 Mbps of data rate (11 Mbps * 3 networks) to be shared among common users across the coverage area (see Figure 2).

This has been proven to adequately distribute sufficient bandwidth to support the majority of applications across many environments, including the relatively dense “cube farms” of large corporations. In today’s environment, common Wi-Fi

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\(^{13}\)While the 2.4 GHz spectral boundaries are common, the regulatory rules are not. For example, 802.11g\textsubscript{OFDM} and 802.11a are currently illegal in the United States, but both are legal in Europe. Bluetooth with 1 MHz channels is legal in almost all relevant countries.
networks support applications such as Microsoft Office, email, server downloads, and FTP applications, by literally dozens of users per AP. Additionally, as user densities increase, Wi-Fi AP transmit power can be decreased, effectively increasing the number of networks within a given area, and therefore increasing the total capacity.

When 802.11g solutions begin entering the market, the available bandwidth provided by Wi-Fi will increase substantially, while maintaining relatively low cost points due to the small incremental development that will be required to produce 802.11g solutions. This will likely provide sufficient throughput for highly data-intensive programs such as computer-aided design / manufacturing, large databases, streaming video, etc.

Wi-Fi throughput levels will support QoS enhancements under the IEEE 802.11e Task Group, although at the expense of a dedicated network or reduced throughput for the existing network. The 802.11e's recommendations will also apply to both 802.11g and 802.11a, which will support the resulting QoS much more effectively.

7.2 5 GHz – 802.11a

The 802.11a standard requires a 16.6 MHz passband for one operating network. The modulation technique allowed in 5 GHz (OFDM) is more efficient than the spread spectrum techniques Wi-Fi uses (more bits/second/ hertz), and provides up to 54 Mbps of data rate to network users. For the US-based 802.11a standard, the 5 GHz unlicensed band covers 300 MHz of spectrum and therefore supports twelve (12) non-overlapping, simultaneously operating networks, as shown in Figure 3.
While a four-AP, 5 GHz network has not been deployed in any commercial environment, 216 Mbps of shared data rate will support all the office productivity applications mentioned for Wi-Fi, plus highly data-intensive applications. Such applications include computer-aided design / manufacturing, large distributed databases, streaming video, as well as QoS enhancements to the 802.11a/b/g standards in the future. It is important to note, however, that the 54 Mbps data rate is within a relatively small coverage area, and that high bandwidth users outside that area would require either more APs for increased coverage, or be subject to reduced throughput.

7.3 Conclusion - Available Spectrum and Spectral Efficiency

The 5 GHz unlicensed band provides over three times as much spectrum as the 2.4 GHz band, and 802.11a provides almost five times the data rate of currently available Wi-Fi solutions. This leads to a vast difference in the number of networks that may be deployed in a single area (12 to 3), and the corresponding data rate amount. However, a few considerations must be taken into account.

First, according to many Wi-Fi installations, an 11 Mbps data rate seems to be sufficient for today's office environment and common network applications, leading one to doubt the urgency of higher bandwidth. Second, although both Wi-Fi and 802.11a can support 20 to 30 users in both theory and recommended practice [LU01], market data shows that the penetration of APs to clients is very low: one AP to every seven clients is the average [CIS00b; VDC01]. This indicates that common wireless network deployments may be far below capacity in terms of actual users, and therefore not suffering a lack of capacity.

So while 5 GHz solutions are clearly dominant in terms of throughput, spectral efficiency, and available spectrum, current network deployments and usage models indicate that Wi-Fi meets the current market and user needs. Therefore, it is logical that IEEE-802.11a and Wi-Fi's 802.11g speed extensions become more attractive as new applications introduce higher bandwidth requirements, or as a significantly higher ratio of clients to APs becomes common.

8 Network Costs and Deployment

The cost of any network should be looked at from a “total cost of ownership” (TCO) model. This would therefore include the cost of the client devices or network interface cards (NICs), the required APs for desired coverage area, throughput, or user support, and the technical support costs.

8.1 Cost of Network Interface Cards (NICs)

The cost of network interface cards (NICs) for Wi-Fi and 802.11a solutions is currently a topic of heated debate in the industry. Wi-Fi technologies are experiencing significant downward pricing pressure from companies that have exported assembly to low-cost OEM nations. As with any competitive market, this will drive the marginal gain to equilibrium with marginal cost, and eventually companies that cannot effectively compete will exit the market. Meanwhile, the customers will benefit enormously as more features are built into every card at similar or declining costs. This same market dynamic will likely hold true for 802.11g solutions since the core technology enhancement is only slightly more expensive than existing Wi-Fi technology, and will be produced by the same companies currently producing the Wi-Fi chipsets. What
premiums do exist will likely be quickly eroded by low-cost competition.

The 802.11a market, on the other hand, is in its nascent growth phase. Technical and market analysis indicates that an 802.11a NIC should cost roughly three times as much as a Wi-Fi NIC [CI00c]. Over the next few years, we expect the number of 5 GHz providers to increase dramatically, thus driving down the cost for 802.11a NICs to levels closer to Wi-Fi. In the immediate term, however, Wi-Fi's forecasted volumes, IC integration levels, and technology maturity levels will allow it to continue to offer significantly lower prices than 802.11a.

8.2 Cost and Number of Access Points

APs are historically high-priced, high-margin devices. However, as with Wi-Fi NICs, low-cost entrants to the Wi-Fi market are beginning to apply pressure to these margins as well. Again, this will continue to increase the value to the end user, as companies must compete on both price and value. And again, 802.11g technology is likely to experience the same market dynamics, thus driving its prices to near parity with Wi-Fi APs. Emerging 802.11a APs, however, are likely to be generally more expensive than Wi-Fi and 802.11g APs.

A more important aspect of AP cost however, is the number of APs needed to cover similar areas. Because 802.11a APs operate in the 5 GHz unlicensed bands, the physics of radio wave propagation become a significant factor, and an 802.11a AP will cover only about a fourth of the area covered by a Wi-Fi AP. Referring back to Figure 1, this means that in order to cover similar sized areas, with all factors being equal including throughput, four 802.11a APs are required for every one Wi-Fi AP.

This not only presents a problem with potential deployment costs, but if there is an existing Wi-Fi network, it becomes readily apparent that a simple overlay of 802.11a APs will not suffice, as only a quarter of the current users will receive the 802.11a service, and a much smaller number will receive the 54 Mbps data rate (see Figure 4). There are ways to address this issue, but not without either increasing the 802.11a APs or changing the operating parameters of the pre-existing Wi-Fi network.

Of course, in some instances 802.11a’s restricted range can be an attractive feature. The primary driver is very high-bandwidth requirements in a very dense user environment. A trading floor with multiple networks, or tightly packed PCs running graphics-intensive applications might be good examples of this type of scenario.

Deployment of more than three networks in a confined area is another example of where reduced range would be attractive. As shown in Figure 2, only three simultaneously operating Wi-Fi networks can overlap without causing interference to each other. Outdated Wi-Fi APs do not have adjustable transmit power, thus representing a capacity ceiling for any area smaller than Wi-Fi’s 100m radius coverage. New Wi-Fi APs allow the user to scale transmit power and thus reduce the coverage footprint thereby avoiding this potential problem; but it remains a fact that the 2.4 GHz band can only support three overlapping, simultaneously operating Wi-Fi networks. The 5 GHz band, on the other hand, can support up to 12 overlapping 802.11a networks, providing for a large amount of potential throughput in a very small area. However, at this time we do not believe there is a common example of where this amount of throughput would be applicable.

8.3 Cost of Support - Certified Interoperability (Wi-Fi)

One key cost component often overlooked when deploying new technology is the cost of technical support. While many companies are not able to track the cost of a technician trouble ticket, this is a tangible component of the total cost of ownership of any piece of technology, and should be a consideration in deployment of any new technology.

In terms of managing the potential support costs for deploying a wireless LAN, one of the possibilities is clearly superior: Wi-Fi. The key differentiator between Wi-Fi and all other past and future wireless LAN technologies is the Wi-Fi brand itself. This is far more than a simple brand, because it is in fact a rigorous certification process that guarantees interoperability with other Wi-Fi certified products [WECA01].

As mentioned in section 1, the guaranteed interoperability of Wi-Fi certified products was highly instrumental in launching the overall WLAN market. Up to the point of Wi-Fi’s ratification and implementation, IT managers were reluctant to adopt WLAN technologies for fear of them becoming obsolete, and because of the associated overhead support costs of configuring multiple vendors’ solutions for interoperability.

Because this proved to be so critical to Wi-Fi, both 802.11g and 802.11a technologies are currently being evaluated for
similar certification processes. This is a time-consuming process, but it is likely to be approved and implemented in less than 12 to 18 months from the publication date of this paper. For this reason, it is likely that initial support costs for deploying these technologies will be high relative to Wi-Fi based solutions.

9 Overall Conclusions

As more and more companies adopt WLANs, the resulting benefits become easier to quantify. According to Gartner publications, the economic benefits of WLANs can add up to as much as $16,000 in savings per user compared with wired alternatives [TEC01]. Given that Wi-Fi is the most widely deployed WLAN standard, this tangible cost benefit is likely due in large part to its growing adoption as a mainstream, horizontal application—and the market shows no signs of slowing.

Wi-Fi’s 11 Mbps data rate provides a good user experience in the majority of existing wireless networks, and with speed extensions from 802.11g and 802.11a on the horizon, WLANs will be able to provide bandwidth and capacity for continued user growth and new generations of applications.

The value of both 802.11g and 802.11a is very clear. Wi-Fi’s 802.11g-speed extension will provide the necessary data rate speed enhancement to allow current Wi-Fi users to deploy QoS and other high-bandwidth applications, while maintaining backward compatibility with Wi-Fi. And as 802.11a matures, it will provide greater overall capacity for bandwidth-intensive, smaller coverage areas.

Based on these clear value propositions, we expect to see mixed-standard enterprise environments in which both 802.11a and Wi-Fi-based technologies coexist. High-density, high-bandwidth common areas will be served by 802.11a—lunchrooms, conference rooms, team rooms, etc.—and lower-density, greater coverage areas will be served by Wi-Fi-based technologies (Wi-Fi and 802.11g).

A mixed-standard environment implies that client devices should be able to roam between 802.11a and Wi-Fi networks. We believe that as greater numbers of competitors enter the 5 GHz market, 802.11a prices will come down, and dual-mode clients and APs will become prevalent. These dual-mode devices will allow IT departments to benefit from the higher-capacity, higher-bandwidth 802.11a networks, while continuing to leverage the basic throughput, lower cost, and lower risk of Wi-Fi-based networks.
Appendix A—Comparison of radio wave propagation at 2.4 and 5 GHz frequencies

While the propagation characteristics of the 5GHz band has not been studied as extensively as the cellular and PCS bands, there is still an adequate body of analysis and measurements that can be drawn from to create useful path loss models. 

The physics principle of free space propagation found in Theodore S. Rappaport’s “Wireless Communications: Principles & Practice” states that as an electromagnetic wave’s length ($\lambda$) grows shorter (i.e., higher frequency), the path loss of that wave increases according to a square law relationship [RAP01]. Also from electromagnetic wave propagation theory, the path loss increases proportionally with the square of the distance between transmitter and receiver in free space. Since 5 GHz radios operate at little over 2 times the frequency of 2.4 GHz radios, it can be shown that the same link budget can only be sustained over about half the distance as a comparable 2.4 GHz system. This is represented by the equation below and Figure 5.

$$l_x = K(d^N/\lambda^2) \quad [\text{often expressed in decibels as } l_x^{(db)} = KL + 10N \log_{10}(d) + 20 \log_{10}(f_x)]$$

OR

$$d = \left[ \frac{(l_x \cdot \lambda^2)}{K} \right]^{1/N}$$

Where:

- $l_x$ = path loss
- $x$ = frequency band or standard (“a” for 802.11a or “b” for Wi-Fi and 802.1.1g)
- $K$ = constant
- $KL$ = constant for loss in dB = 32.44 when $f$ is in MHz and $d$ is in kilometers
- $d$ = distance
- $N$ = attenuation factor: $N=2$ for free space; $N>2$ in most practical environments
- $\lambda$ = wavelength
- $f$ = frequency = $c/\lambda$
- $c$ = speed of light = $3 \times 10^8$ meters/second (free space)

![2.4 GHz Radio Wave Range is At Least 2 Times Greater than that of 5 GHz Systems](image)

Figure 5: Comparative Free Space Path Loss Between 2.4 and 5 GHz Systems

Rappaport and Durgin’s IEEE study of 5 GHz indoor path loss in urban homes [JCS01, DUR01] has been used primarily in this paper with slight modifications; it is an empirical model that is an extension of the free space path loss given above that simplifies to:

$$L_a = 57 + 34 \log_{10}(d)$$

Where $d$ is in meters and the 5.x GHz band is assumed.
Appendix B— WLAN Throughput Calculations

The wireless LAN data rate numbers used throughout this paper refer to data rate at the top of the MAC, and use the overhead and throughput calculations shown in the table below.

Table 5: Throughput Calculation by Standard

<table>
<thead>
<tr>
<th>Units</th>
<th>Wi-Fi™, 11 Mbps, long preamble</th>
<th>Wi-Fi™, 11 Mbps, short preamble</th>
<th>802.11a</th>
<th>802.11b OFDM</th>
<th>802.11g PBCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW min</td>
<td>slow ACK</td>
<td>fast ACK</td>
<td>slow ACK</td>
<td>fast ACK</td>
<td>slow ACK</td>
</tr>
<tr>
<td>SIFS</td>
<td>micro sec</td>
<td>31</td>
<td>31</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>Slot duration</td>
<td>micro sec</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>DIFS</td>
<td>micro sec</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Average Backoff Duration</td>
<td>micro sec</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>DATA MPDU Payload size</td>
<td>Mbps</td>
<td>54</td>
<td>54</td>
<td>54</td>
<td>54</td>
</tr>
<tr>
<td>DATA MPDU Overhead</td>
<td>Mbps</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>DATA PPDU Overhead</td>
<td>micro sec</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>DATA PPDU Duration</td>
<td>micro sec</td>
<td>1207</td>
<td>1207</td>
<td>1207</td>
<td>1207</td>
</tr>
<tr>
<td>SIFS</td>
<td>micro sec</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>ACK MPDU Rate</td>
<td>Mbps</td>
<td>2</td>
<td>11</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>ACK MPDU Length</td>
<td>B</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>ACK PPDU Overhead</td>
<td>micro sec</td>
<td>152</td>
<td>152</td>
<td>152</td>
<td>152</td>
</tr>
<tr>
<td>ACK PPDU Duration</td>
<td>micro sec</td>
<td>224</td>
<td>224</td>
<td>224</td>
<td>224</td>
</tr>
<tr>
<td>Backoff + DATA + SIFS + ACK duration</td>
<td>micro sec</td>
<td>1273</td>
<td>1273</td>
<td>1273</td>
<td>1273</td>
</tr>
<tr>
<td>Effective throughput</td>
<td>Mbps</td>
<td>1.02</td>
<td>1.02</td>
<td>1.02</td>
<td>1.02</td>
</tr>
</tbody>
</table>

Throughput as % of DATA PHY rate % 57% 58% 63% 65% 57% 58% 44% 45% 46% 49%
MIDU + PPDU overhead (DATA + ACK) % 22% 23% 14% 14% 21% 21% 22% 22% 20% 20%
Backoff overhead (average backoff + SIFS) % 19% 20% 21% 22% 30% 30% 32% 32% 32% 33%

Table Source: Mobilian Corporation

*802.11g OFDM - assumes same parameters as 802.11a with additional short preamble
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